Tolerancing Method and Metrics for Imaging Spectrometers

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Purpose

Standardized Assessment of Imaging Spectrometers

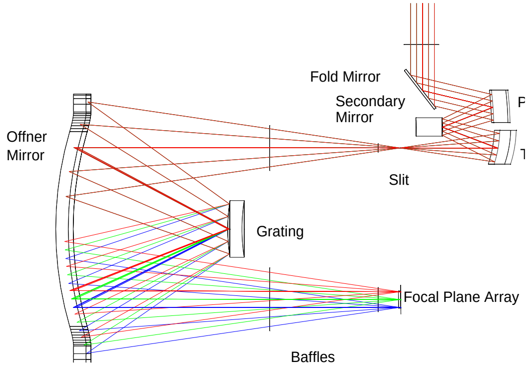
- Imaging Spectrometer Performance Metrics
  - Along-Track, Cross-Track, and Spectral Response Functions
  - Smile and Keystone
- Useful for comparison of imaging spectrometers
- Can be used in the entire process of building a sensor
  - Design
    - Example: P. Mouroulis et al. Opt. Eng. 46(6) 2007, J. F. Silny, Proc. SPIE 9976, 2016
  - Tolerancing
  - Alignment
    - Example: H. A. Bender, Proc. SPIE 8158, 2011
  - Assessment of Final Sensor
    - Example: P. Mouroulis et al: Appl. Opt. 53(7), 2014
- Purpose of this talk:
  - **Outline a method to tolerance imaging spectrometers using the response functions, smile, and keystone.**

Overview

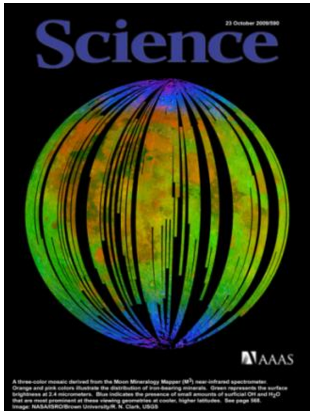
- Background
  - Imaging Spectrometers
  - Performance Metrics
    - Along-Track Response Function (ARF)
    - Cross-Track Response Function (CRF)
    - Spectral Response Function (SRF)
    - Smile and Keystone
- Tolerancing Setup
  - Where to apply the response functions.
  - Metric Functions
  - Summary
- Method
- Error Budget Example

Offner Imaging Spectrometers

Moon Mineralogy Mapper (M3) On Chandrayaan 1



Launched Oct. 2008



Pieters et al, Science 326, 2009
Green et al, J. Geophys. Res. Planets 116, 2011
Mouroulis et al, Opt. Engineering 46, 2007

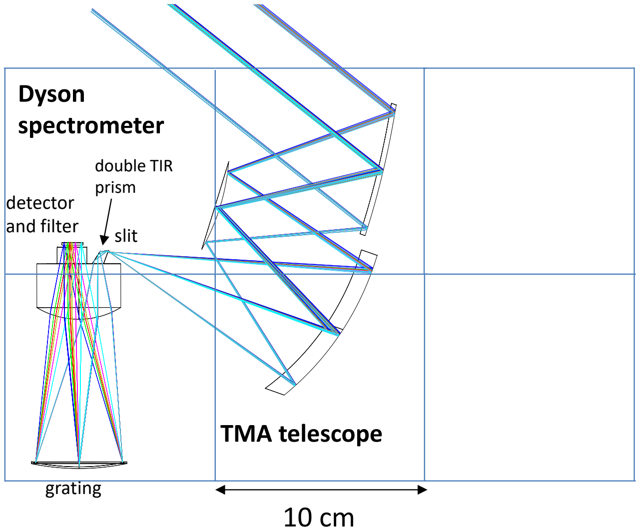
Ultra Compact Imaging Spectrometer (UCIS)

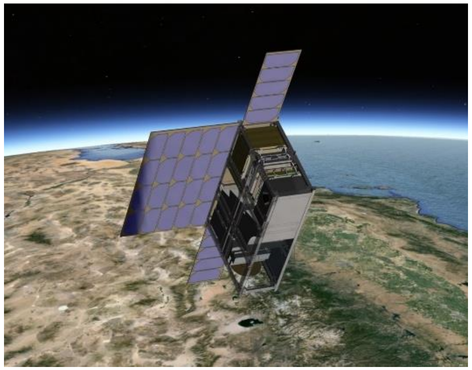
Miniaturized full-range (500-2600 nm) spectrometer system

Van Gorp et al, J. Appl. Rem. Sens. 8, 2014

Dyson Imaging Spectrometers

Snow and Water Imaging Spectrometer (SWIS)

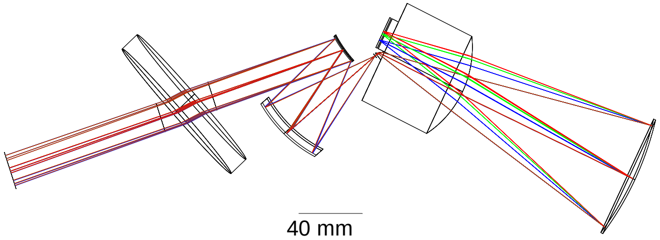


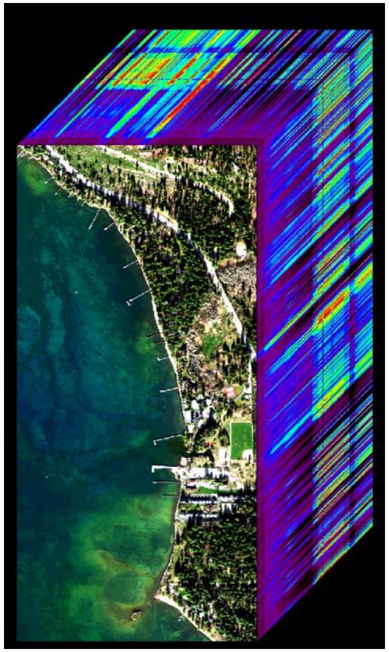


SWIS CubeSat, Artist's concept

Mouroulis et al, Proc. SPIE 9222, (2014)
Bender et al, Proc. SPIE 9881, (2016)

Portable Remote Imaging Spectrometer, (PRISM)



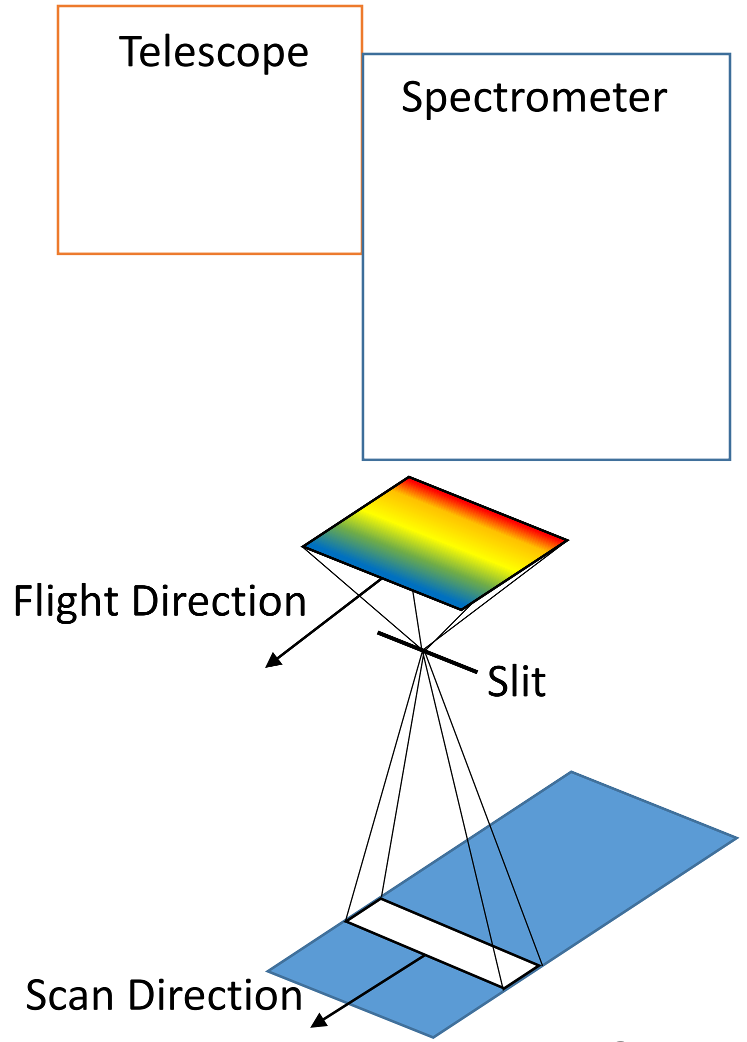


Mouroulis, Green & Wilson, Opt. Express 16, 2008
Mouroulis et al, Appl. Opt. 53, 2014
https://prism.jpl.nasa.gov

Why use Response Functions

To first approximation, Pushbroom imaging spectrometers are

- Two optical systems
  - Telescope and Spectrometer
- Separated by an intermediate image plane at the slit.
- Decoupled in the scan axis.
  - The slit decouples the telescope from the spectrometer along the scan axis.
  - Telescope resolution dominates the spatial resolution along the scan axis.
  - Spectrometer resolution dominates the spectral resolution.
- Coupled in the orthogonal axis
  - The combined telescope and spectrometer determine the resolution along this spatial axis.
- Three response functions are needed.

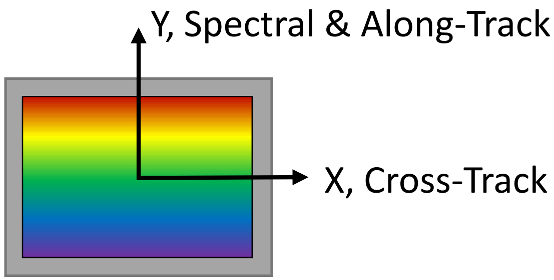


Mielenz, J. Opt. Soc. Am. 57, 1967
Mouroulis & Green, Proc. SPIE 6667, 2007

Response Function Definition

To first approximation (incoherent approximation)

- Along-Track Response Function (ARF)
  - Convolution of
    - **Telescope Y**-line spread function
    - Slit
    - Motion blur term (optional)
- Cross-Track Response Function (CRF)
  - Convolution of
    - **Full System X**-line spread function
    - Detector pixel response
- Spectral Response Function (SRF)
  - Convolution of
    - **Spectrometer-only Y**-line spread function
    - Slit
    - Detector pixel response



Focal Plane

Uniformity of Response
Smile and Keystone

- Smile and Keystone
  - Geometric errors of the spectrum registration.
- Uniformity includes variation in the shape of the response functions.
  - Reduce chromatic variations of the spatial response functions, ARF and CRF
  - Reduce spatial variations of the spectral response function, SRF

Tolerancing Run Setup

- Where performance metrics are applied

Telescope	Spectrometer
ARF	**SRF, Smile, Keystone**

CRF

- Six Tolerancing Runs
  - Three Optical Models
    - Telescope
    - Spectrometer
    - Full System
  - Two Use Cases
    - Fabrication & Alignment
    - In-Use Thermal & Vibration

Tolerancing Merit Functions

- Smile and Keystone
  - Simple and rapidly calculated
  - Used as a tolerancing merit function
- Response Functions Full Width Half Max (FWHM)
  - Not rapidly calculated
  - Not used directly
- Proxy Merit Functions
  - Used to speed up tolerancing computation.
  - Examples: Wavefront, Enslitted Energy.
  - Criteria
    - Readily calculated
    - Appropriate for the optical system and stage of tolerancing
    - Correlate with the metric of interest

Tolerancing Summary

System	Process	Compensators	Feeds into	Merit function
Telescope	Fabrication & Alignment	Telescope back focus	ARF, CRF	Telescope enslitted energy
Telescope	In Use Thermal & Vibration	None	ARF, CRF	Telescope enslitted energy (no mid freq. error)
Spectrometer	Fabrication & Alignment	FPA: focus, tip & tilt	CRF, SRF, Smile, Keystone	Smile, keystone, wavefront
Spectrometer	In Use Thermal & Vibration	None	CRF, SRF, Smile, Keystone	Smile, keystone, wavefront
Full system	Final Alignment/ Verification	Telescope focus (at slit), FPA focus	CRF, ARF, SRF	RMS Spot size in Y for telescope and in X for full system
Full system	In Use	Focus (optional)	CRF, ARF	RMS Spot size in Y for telescope and in X for full system

Method

- Propose approximate optical component tolerances
  - Examples: displacements, radius of curvature, irregularity, tip/tilt
- Setup Tolerancing analysis for each optical system and process
- Run a Monte Carlo tolerancing analysis
  - Save 100's of perturbed systems.
  - Calculate the response functions for the worst systems.
    - Example: 90^{th} percentile perturbed systems.
- Revise component tolerances and repeat as needed.
- Develop an error budget
  - Use the increase to the response function calculated for the 90^{th} percentile systems.

Error Budget Example

	Spatial Sampling *urad, along slit*	Spectral Sampling *nm, across slit*	Spectral Resolution *nm FWHM*	Along-Track Resolution *times IFOV @FWHM*	Cross-Track Resolution *times IFOV @FWHM*	Smile *spectral center vs. field*	Keystone *cross-track center vs. λ*
Requirement	17.1 ± 2%	≤ 5	≤ 7	≤ 1.3	≤ 1.3	≤ 10%	≤ 10%
Design	16.97	4.46	6.67	1.24	1.24	1.80%	2.40%
Tolerance Budget #1: fabrication / alignment, compensated	0	0	0.03	0.036	0.024	2.30%	3.00%
Tolerance Budget #2: thermal & other in-use perturbations, no compensation	0	0	0.03	*0.043	*0.1	0.20%	0.70%
Tolerance Budget #3: in-use with focus compensator	-	-	-	0.013	0.016	-	-
Slit width (± 0.3 micron width)	-	-	0.04	0.01	-	0.20%	-
Grating Fabrication Errors	-	.001	-	-	-	-	-
Telescope Focal Length	0.6%	-	-	-	-	-	-
FPA response knowledge	-	-	0.3	-	0.3	-	-
Test/Model Uncertainty	-	-	0.2	0.1	0.1	1%	2%

Conclusion

- Outlined a method to tolerance imaging spectrometers.
- Based on imaging spectrometer performance metrics.
  - Response functions, smile and keystone.
- Showed when to apply each performance metric.
- Gave suitable proxy merits to speed up tolerancing.
- Gave an example Error Budget using imaging spectrometer metrics.

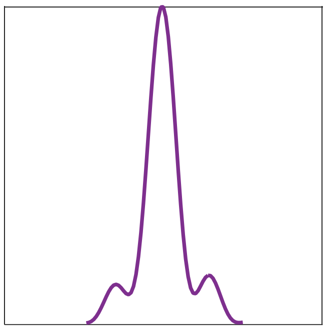
References

- [1] P. Mouroulis, R. Glenn Sellar, D. W. Wilson, J. J. Shea, and R. O. Green: "Optical design of a compact imaging spectrometer for planetary mineralogy", Opt. Eng. 46(6) 063001 (2007)
- [2] J. F. Silny: "Resolution modeling of dispersive imaging spectrometers", Proc. SPIE 9976, 99760A-1 (2016)
- [3] H. A. Bender, P. Mouroulis, M. L. Eastwood, R. O. Green, S. Geier, and E. B. Hochberg: "Alignment and characterization of high uniformity imaging spectrometers", Proc. SPIE 8158, 81580J (2011)
- [4] P. Mouroulis et al: "Portable Remote Imaging Spectrometer coastal ocean sensor: design, characteristics, and first flight results", Appl. Opt. 53(7) 1363-1380 (2014)
- [5] T. Skauli: "An upper-bound metric for characterizing spectral and spatial coregistration errors in spectral imaging," Opt. Express 20, 918-933 (2012)
- [6] H. A. Bender, P. Mouroulis, R. O. Green, D. W. Wilson: "Optical design, performance and tolerancing of next-generation airborne imaging spectrometers", Proc. SPIE 7812, 78120P (2010)

Backup

Along-Track Response Function (ARF)

Telescope Only



LSF(y)

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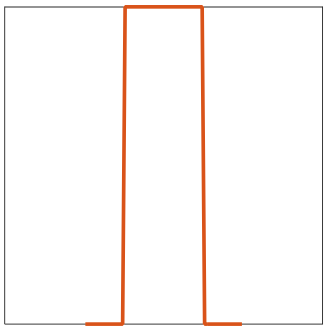

Slit

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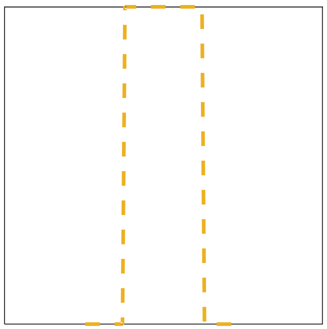

Motion Blur (optional)

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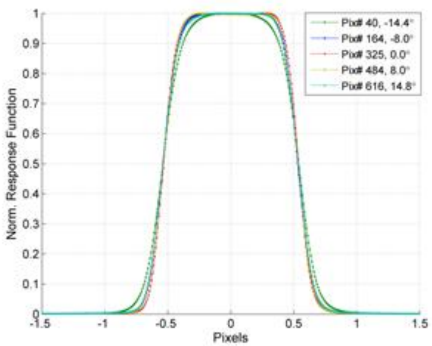
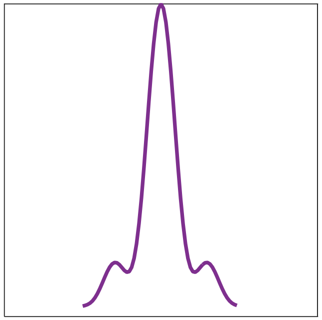


ARF before Motion Blur

- Convolution of the Telescope Y-Line Spread Function and the Slit (and optionally, a Motion Blur Term)

Cross-Track Response Function (CRF)

Combined System



LSF(x)

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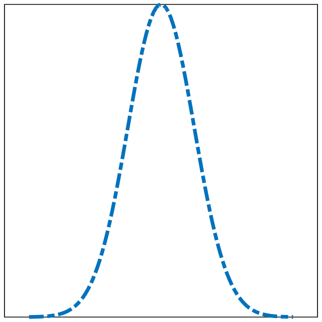

Detector Pixel Response

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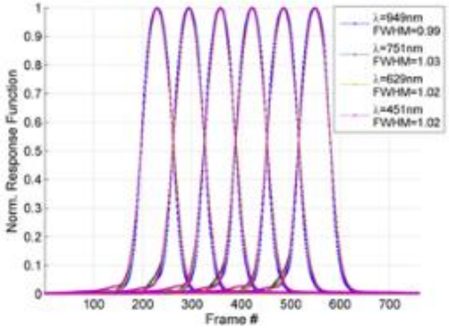
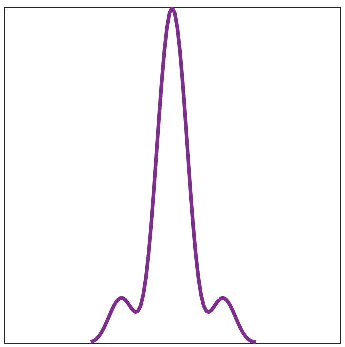


CRF

- Convolution of the Full System X-Line Spread Function and the Detector Pixel Response

Spectral Response Function (SRF)

Spectrometer Only



LSF(y)

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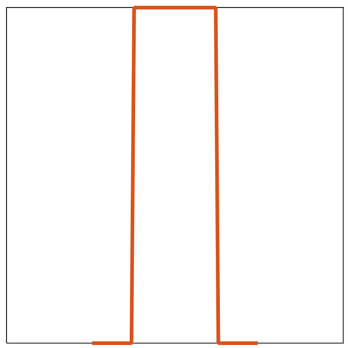

Slit

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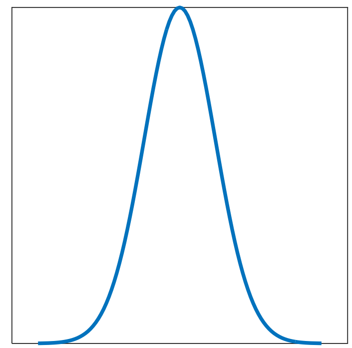

Detector Pixel Response

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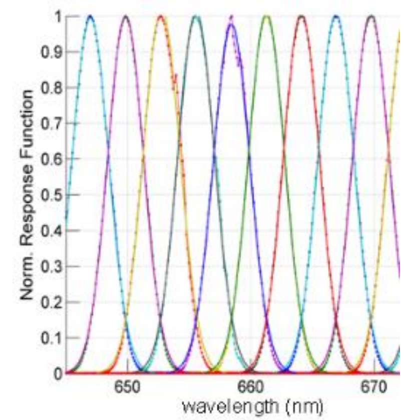

SRF

- Convolution of the Spectrometer only Y-Line Spread Function, the Slit, and the Detector Pixel Response.